CHAPTER 3

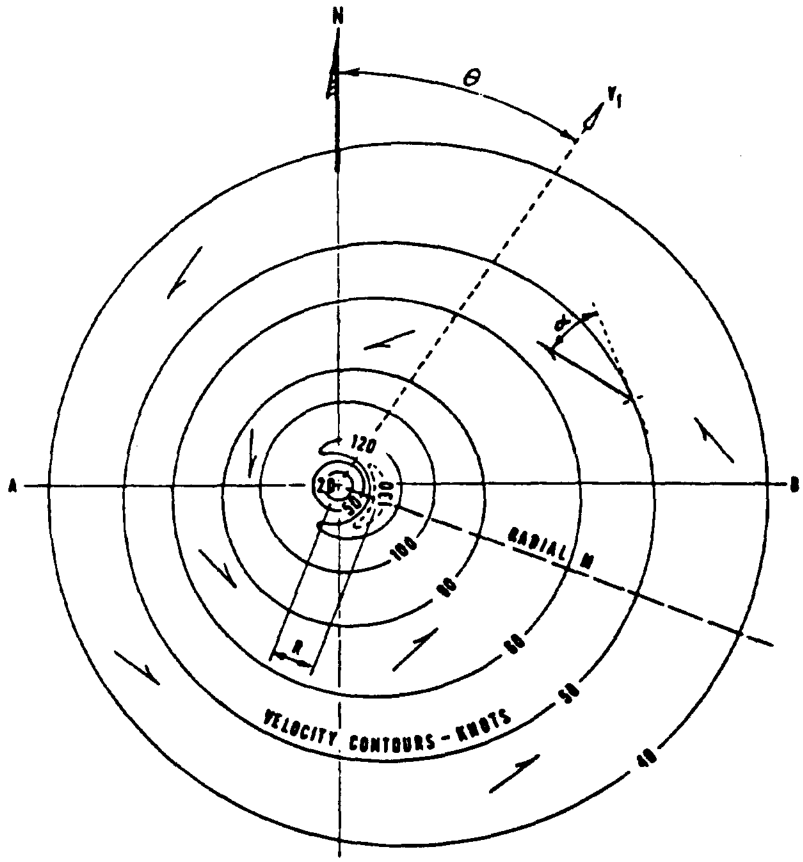
STORM SURGES

3-1. Storm Surge Generation. Storms are atmospheric disturbances characterized by one or more low pressure centers and high winds, frequently accompanied by precipitation of varying intensity. An important distinction is made in classifying storms: a storm originating in the tropics is called a "tropical storm;" a storm resulting from the interaction of a warm and a cold front is called an "extratropical storm;" and a severe tropical storm is referred to as a "hurricane" or "tropical cyclone" when the maximum sustained winds equal or exceed 75 miles per hour. Unlike extratropical storms and less severe tropical storms, hurricanes are well organized with respect to the wind patterns. The spatial scale of hurricanes is typically small in comparison to major extratropical storms. Both hurricanes and extratropical storms are capable of causing a significant rise or possible fall in the normal water level in coastal waters. A brief overview of procedures for estimating and predicting these abnormal water levels is provided in this chapter.

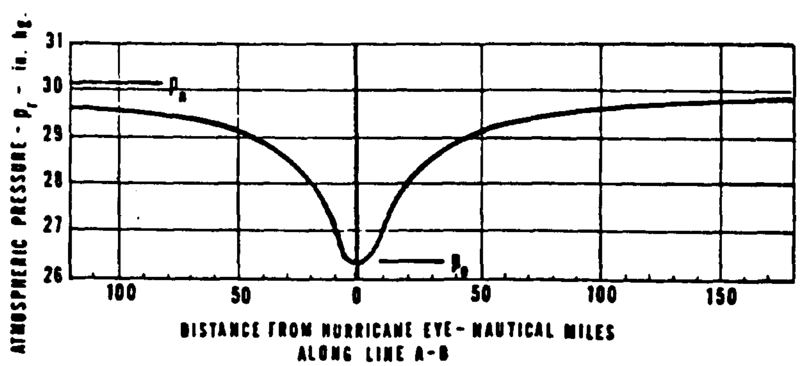
a. Tropical Storms and Hurricanes. Pronounced water level changes due to tropical storms may occur anywhere along the Gulf coast and anywhere from Cape Cod to the southern tip of Florida on the east coast of the United States. Occasionally, the southern coast of California on the west coast experiences changes in water level as a result of a tropical storm, but these are usually small due to the narrow continental shelf in that region.

(1) Many dangerous and destructive tropical storms have occurred along the Atlantic and Gulf coast areas of the United States. In many coastal areas, a severe storm causes the water level to rise in excess of 15 ft above the normal level on the open coast and even higher in estuaries and other inland areas. The elevated coastal waters due to surges provide a higher level in which short-period surface waves can propagate, thus subjecting beaches and structures to wave forces not ordinarily experienced. Surges coupled with the action of surface waves are responsible for the greatest damage to coastal areas. They can destroy or severely damage dwellings, business establishments, commercial properties, and docking facilities, erode beaches, displace stones or concrete armor units on jetties, groins, or breakwaters, undermine structures via scouring, cut new inlets through barrier beaches, and shoal navigational channels. The latter shoaling problem can result in hazards to navigation which impede vessel traffic and hamper harbor operations. The duration of the surge as well as the elevation is important for beach erosion and channel shoaling considerations.

(2) The wind pattern of a hurricane is more or less circular, with winds revolving counterclockwise in the northern hemisphere about the storm center or eye (not necessarily the geometric center). Winds in hurricanes blow spirally inward and not along a circle concentric with the storm center. Wind isovel patterns and wind directions are illustrated in Figure 3-1(a). The eye is characterized as an area of low atmospheric pressure and light winds. Atmospheric pressure increases with distance from the eye to the periphery or outskirts of the hurricane. Highest wind speeds usually occur in the right quadrants of the hurricane at a distance varying from about 4 to 70 nautical miles from the center. In all directions outward from the eye of the



a. Wind isovel pattern and pertinent parameters



b. Pressure profile

Figure 3-1. Sketch showing hurricane parameters hurricane, wind speed increases rapidly to a maximum and then decreases with distance to the outskirts of the storm. The best single index for estimating the surge potential of a hurricane is the atmospheric pressure within the eye and is referred to as the central pressure index (CPI). In general, the lower the CPI, the higher the wind speeds. Other important parameters of a hurricane with regard to the surge potential are the radius of maximum winds R which is an index of the size of storm, the speed of forward motion of the storm system V_F, and the track direction θ in which a hurricane moves (measured clockwise from north).

(3) In engineering studies hypothetical hurricanes are frequently used to assess the levels of flooding for a predetermined degree of severity. These storms are derived based on the specification of meteorological parameters R, V_f, P_o, P_n, θ, and α in which P_o is the central pressure, P_n is the peripheral pressure, and α is the inflow angle (see Figure 3-1). It has been general practice to use invariant meteorological parameters for any given hypothetical hurricane prior to the storm making landfall. Thus, such storms are classified as constant valued hurricanes. Particular hypothetical hurricanes which have been used in some engineering investigations are referred to as the Standard Project Hurricane (SPH) and the Probable Maximum Hurricane (PMH). The SPH is defined as a hurricane having a severe combination of values of meteorological parameters that will give high sustained wind speeds reasonably characteristic of a specified coastal location. A PMH, on the other hand, is defined as a hurricane having a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location. Recurrence intervals for the SPH and PMH are not assigned due to the uncertainties involved in establishing the frequencies. The SPH is used in the design of coastal works where a rather high degree of protection is required. The PMH was developed in connection with the design of nuclear power generation plants sited in coastal areas.

(4) Hypothetical hurricanes with more frequent recurrence intervals than the SPH are also used to estimate the frequency and levels of flooding. The flood frequencies are established by calculating the water levels produced by numerous hypothetical hurricanes and assessing the recurrence intervals by application of the joint probability method

b. Extratropical Storms. Large changes in water level may occur along the northern part of the east coast of the United States as a result of extratropical storms in which strong winds blow from a northeasterly direction. These storms are commonly referred to as "northeasters." Northeasters are important from the standpoint of design considerations on the east coast. However, an acceptable technique for specifying the wind fields for design storms is not presently available.

3-2. Prediction Models.

a. Numerical Prediction Models. Storm surge prediction for design is usually based on a theoretical approach, although in some cases sufficient data may be available at a site to warrant the historical approach discussed in Section 3-2.b. In the use of the theoretical approach, a number of mathematical or numerical models have been developed for simulating the storm wind fields and the storm-induced water motions. Computer programs are used in conjunction with the models to perform the necessary calculations. The models are formulated based on the governing hydrodynamic equations.

(1) The approach is also applicable to problems involving the SPH and PMH. In all studies concerned with water level determinations in coastal areas as a result of hurricanes the SPH is to be a part of the analysis except in the case that the design is to be based on the PMH.

(2) The magnitude and frequency of occurrence of storm-induced water levels coupled with the effects of astronomical tide is established by synthetic methods. The methods consist of an indirect approach in which water level data are generated from a rather large ensemble of synthetic storms via numerical computations, and flood frequencies are established based on an analysis of the computed water level data. A large variety of synthetic storms may be derived by utilizing various combinations of storm parameter probabilities that are characteristic of a given coastal location. Historical data of the individual storm parameters are used in the determination of the statistical distribution of the parameters. The statistical concept referred to as the joint probability method is used to determine the magnitude and frequency of occurrence of water levels when using the synthetic approach.

(3) The primary advantage of this method is that a rather large data base can be generated based on various combinations of the storm parameters. Also, the storm parameters are reasonably well defined due to the availability of regional historical data and the present technology available for describing meteorological aspects of storms, particularly hurricanes. In addition, computational hydrodynamics have advanced to the state that water levels can be computed with a reasonable degree of accuracy.

b. Historical Prediction Models. An accumulation of water level data from past storms over a span of many years at a given location may provide sufficient information for predicting design water level at that location. Rather long-period records of water level data are required to confidently predict the frequency and magnitude of flood levels by the historical data approach since the underlying assumption for this method is that past events are representative of future events.

(1) A subjective decision must be made with regard to whether the historical method should be used or not used for a given engineering study. This decision depends on the quantity and quality of data that are available as well as confidence that the sample data are representative of future events. With regard to the quantity of data, item 5 indicates that as a rule of thumb, at least N/2 years of data are required to confidently predict the annual percent chance of occurrence of an event with an average return interval of N years. This implies that data recorded over a period of 50 years would be required to confidently predict the elevation of the water surface with a 1 percent chance of occurrence.

(2) The historical method is considered applicable to various sites along the New England coast and other coastal areas where relatively long-term water level records exist. In general this method has limited usage due to the lack of sufficient historical data.

(3) From a statistical point of view, historical flood levels are not all from the same population. This is due to the observed levels that can be produced from either extratropical storms, tropical storms, or severe tropical storms (hurricanes) coincident with fluctuations caused by the astronomical tide. Consequently, mixed populations are always involved. As an approximation, however, it is generally considered appropriate to treat the entire water level record as a single population provided that the record is of sufficient length. In the event that a relatively short-term record, 20 years or less, is analyzed, the predicted astronomical tide should be extracted from the observed water levels and replaced with the mean high tide. The latter modification is recommended for the purpose of ensuring that the tide component is of sufficient magnitude.

c. Simplified Prediction Methods.

(1) Storm surge in an enclosed basin. The tilting of the water surface is an enclosed basin (e.g., lakes and reservoirs) caused by wind shear stress is known as wind setup. The water surface is above the normal still-water level (SWL) on the leeward side of the basin and below the SWL on the windward side. Wind setup can be reasonably estimated for basins of simple shape and long compared to their width, assuming motion in the long axis only. Wind setup, the rise in the water level at the leeward end relative to the SWL, may be estimated by

$$S = \frac{U^2 F}{1400\ d} \tag{3-1}$$

where

S = setup relative to the SWL (ft)

U = wind speed (mph)

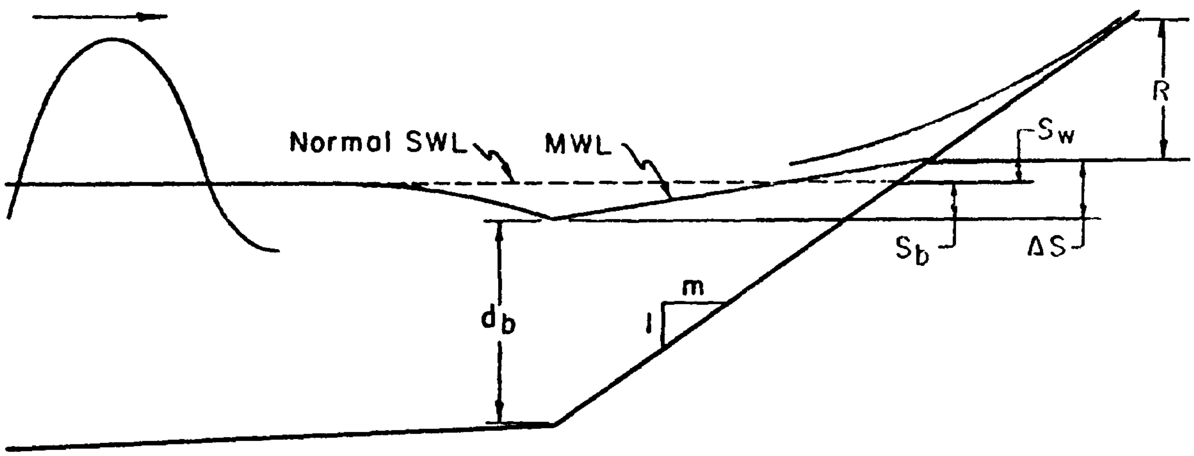
F = fetch (miles)

d = average water depth over fetch (ft)

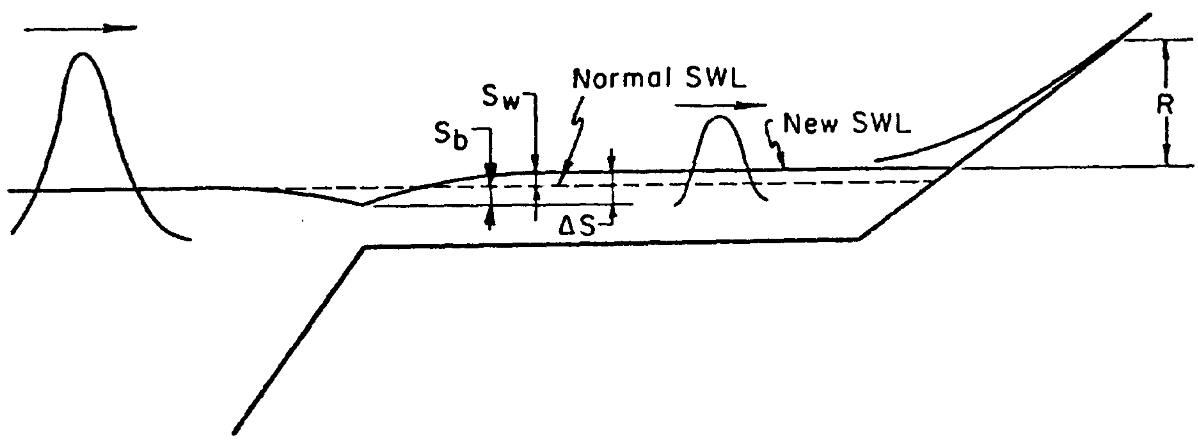
Wind speed is assumed by default to represent an elevation of 33 feet (10 meters). The coefficient in equation 3-1 is an average value based on previous investigations. The coefficient may vary for different basins. Advection of momentum, atmospheric pressure variation, astronomical effects, and precipitation are neglected. Also, a steady state is assumed to exist. Setup cannot be estimated satisfactorily by this method if natural barriers, such as islands, affect the horizontal water motions.

(2) Wave setup. Wave setup and setdown are the change in the mean water level due to the excess onshore momentum of the waves. At the shoreline there is normally a setup of the water surface relative to the SWL; whereas at the breaker line there is a setdown relative to the SWL (Figure 3-2).

(a) For monochomatic waves, the setdown at the breaker line S_b can be estimated



a. On a beach



b. On a berm or reef

Figure 3-2. Definition sketch of wave setup

$$S_b = -\frac{g^{1/2}\left(H_o'\right)^2 T}{64\pi\, d_b^{3/2}} \tag{3-2}$$

where

S_b = setdown at the breaker line relative to the SWL (ft)

T = wave period (sec)

H = equivalent unrefracted deepwater significant wave height (ft)

d_b = water depth at the breaker line (ft)

g = acceleration of gravity (ft/sec^2)

An approximation of the total difference in water surface elevation between the breaker line and the mean shoreline s, setup plus setdown, is expressed as

$$s = 0.15\, d_b \tag{3-3}$$

based on laboratory data of item 113. Combining equations (3-2) and (3-3) yields an expression for the wave setup at the mean shoreline S_w as follows:

$$S_w = 0.15\, d_b - \frac{g^{1/2}\left(H_o'\right)^2 T}{64\pi\, d_b^{3/2}} \tag{3-4}$$

where the water depth of breaking is given by the expression

$$d_b = \frac{H_b}{\dfrac{1.56}{1 + e^{-19.5m}} - \dfrac{43.75\,(1 - e)^{-19m}\, H_b}{gT^2}} \tag{3-5}$$

with m equal to beach slope. Care must be taken to use consistent units for d_b, H_b, g, and T. The wave setup and setdown represent equilibrium conditions which require sufficient time to be established. The exact time to establish equilibrium is unknown, but the Shore Protection Manual (SPM) suggests a minimum duration of 1 hour.

(b) Wave setup should not be confused with wave runup. Runup is the greatest elevation above the SWL reached by the uprush of waves breaking on the shore. Measurements of wa/e runup include the effect of setup.

(3) Atmospheric pressure effect on water level. Table 3-1 gives the water level rise due to atmospheric pressure variation produced by a storm. The water level rise due to the atmospheric pressure can be linearly added to the water level rise due to other factors (eg., wind setup and wave setup).

3-3. Sources of Data for More Detail. Water level data recorded during storm periods may be obtained from a variety of sources. The principal source of

Table 3-1

Atmospheric Pressure Effect on Water Level

Storm Central Pressure mb	in. of Hg	Water Level Rise* ft
900	26.58	3.78
910	26.87	3.45
920	27.17	3.11
930	27.46	2.78
940	27.76	2.44
950	28.05	2.11
960	28.35	1.77
970	28.64	1.44
980	28.94	1.10
990	29.23	0.77
1000	29.53	0.43

*Relative to water level for atmospheric pressure of 1013 millibars = 29.91 inches of Hg.

recorded data is tide records of the NOS. Other sources of recorded data are gages operated by the Corps, USGS, and a few other organizations. High-water marks also provide a means for obtaining maximum water levels. They are, in general, inherently less reliable than measurements obtained from recording gages. Many sources are available for obtaining high-water marks such as those obtained by various government agencies, newspaper accounts, and private organizations. A principal source of high-water marks is poststorm reports prepared by district offices in the Corps. Maximum water levels from high-water marks are usually established from such effects as debris accumulation and mudline discoloration. In open areas these marks generally reflect both the water level rise and the maximum amplitude of short-period surface waves and possibly wave runup. There are no reliable techniques for establishing the true water level rise when surface wave effects are involved. The most preferable high-water marks are those for which surface waves are filtered out, such as pipe gages designed specifically for recording the maximum water level, within buildings, and other sheltered sites.

a. Transposing Data. Unfortunately, water level data are seldom available at the site for which the data are needed in connection with engineering studies. In the event there are sufficient and reliable water level data in the vicinity of the site, it may be possible to estimate the site data based on an adjustment to the existing data at nearby locations. Considerable care must be exercised in transposing the adjusted observed data to a nearby site.

b. More Information. Much more detailed information is given in Engineer Manual (EM) 1110-2-1412.